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COMPENSATION OF LARGE CHANGES IN REACTIVITY BY MEANS OF CORE LATTICE DEFORMATION

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1.

An attempt to prolong core life of power and research reactors results in continuous increase in excess reactivity of clean cores. In light water-cooled and-moderated reactors which are more widely used this excess reactivity is about 0.15 and tends to increase with every new core developed. At the same time methods of excess reactivity compensation are developed and improved: burnable poisons are inserted, mechanical systems (control rods, fuel assemblies, and compensating systems-rods moved in groups) become greater in number and more complex. The present methods, how - ever, have some disadvantages, therefore they cannot be conside- red quite satisfactory. Thus, the use of the most perfect system of burnable poisons cannot ensure the operating excess reactivity required for compensating temperature effect, steady-state poisoning, power changes and "boron disbalance", and mechanical systems, for example, compensating systems, give rise to large power distortions or as systems of a great number of low capture rods with separate drives are too complex and bulky. In addition a system of rods and their drives result in increasing the reactor height required.

There are three possible ways of providing operating excess reactivity:

a) Usual absorbing control system mechanisms: rods, assemblies, compensating systems and their various modifications.

b) Changes in moderator properties during reactor operation, for example, the use of light and heavy water mixturos of various component concentrations, solution of absorbing materials in the moderator and their gradual extraction.

c) Changes in core lattice spacing (or some other deformation of the core).

The use of conventional control mechanisms is easily combined with changes in the moderator properties but it is rather difficult to achieve in the case of core deformations. Any methods of providing operating excess reactivity permit the use of burnable poisons.

The possibilities of traditional compensation systems are well studied and practically they always prove to be rather "rigid", i.e. they contain a small number of highly efficient control mechanisms. Changing the moderator properties during the reactor operation is an example of "soft" control giving rise to minimum power distortions. Control systems of this type begin to find use in some reactors.

The specific features of a possible control system by means of core lattice deformation are being discussed below.

Let us consider a reactor core formed by a regular lattice of cylindrical fuel elements placed in a liquid moderators, say in H_2O. Let the top ends of all elements be fastened in some plane thus that any of them can turn independently around the fastening point. Let, further, these elements pass freely through the spacer plate, the holes in it forming a grid similar to that of fastening points. The lattice and the form of the cylindrical reactor do not depend on the distance between the plane of joints (fastening points) and that of the spacer plate. Let the plate be rotated in the horisontal plane around the reactor central axis. Then the core will have the form of a one-sheet hyperboloid of revolution and the fuel element lattice will be deformed thus that the surfaces of the constant spacing will turn out to be, with a greater accuracy, ellipsoids of revolution having one focus with the hyperboloid that forms the side boundary.

With the given fuel elements and the angle of twisting the reactor form depends on the distance between the spacer plate and the plane of joints, therefore control may be also provided by changing this distance but not with rotating alone. In principle, a case may be considered when the spacing of holes in the spacer plate is different from that of joints and the initial core form is not a cylinder but a truncated cone. However, for design considerations as well as for improvement of power distribution the variants symmetrical or nearly symmetrical relative to the core central plane are of greater interest.

The proposed schemes are not suitable for reactors formed of separate fuel elements cooled by water because of changes in coolant passage area during the core deformation. However, this is not the case in systems with fuel elements enclosed in channels as interchannel water is only a moderator.

The reactivity dependence on the core spacing in a cylindrical reactor is not monotone, it has optimum. When the spacing increases reactivity rises first, and then falls. Therefore to control a reactor by means of the core deformation it is possible to use either the "left" branch of the curve corresponding to the core spacing less than optimum or the "right" one corresponding to the spacing greater than optimum.

It is evident in advance that the maximum efficiency of control for the right branch is limited by nuclear safety considerations. Really, in a heterogeneous reactor increase in lattice spacing causes increase in positive component of temperature effect due to flattening the thermal neutron distribution over the cell. In a system with a great spacing lattice the temperature effect as well as temperature coefficient of reactivity becomes positive near the operating point. Keeping the consideration pointed out in mind it is desirable to make initial lattice spacing not very great.

The minimum spacing for the left branch is determined according to the channel diameter and the possible deformation efficiency depends upon the difference between reactivity with optimum spacing and that with the channels touched. In the case of channels containing little interchannel moderator or in an extreme case of separate fuel elements the power distribution along the reactor axis may turn out to be unstable while twisting. While

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decreasing the coolant passage area the small asymmetry of the lattice and the external form of the core relative to its central plane give rise to a non-uniform neutron flux distribution.

In a reactor with a deformated lattice it is rather difficult to locate conventional quick-response mechanisms of scram and automatic control circuits. A possible design variant may be performed by removal of channels from the region around the reactor axis or by using a group of central channels "twisted" or brounght closer in advance. In addition, one should care not only for efficiency of quick-response control mechanisms but for prevention of great radial neutron distribution distortions. But the greatest difficulty encounted may be the necessity to provide for reliabbility of a great number of kinematic pairs and flexible elements ensuring the movement of channels. In essence, feasability of the compensation system under discussion depends on the possibility to provide for a safe operation of these pairs and elements in the reactor region which is not accessible while in operation.

2.

To describe mathematically the control system by means of "twisting" the core lattice. let us consider a cylindrical reactor, where 2H is an effective height of the reactor and R is an effective radius. If Z = $\pm$ Zo plane is turned to $\pm\ \omega$ angles relative to the vertical axis the cylinder will change into a body limited by a hyperboloid of revolution and a surface that, with reasonable accuracy, may be taken for an ellipsoid. In this body cross-section by the plane passing through the axis Z, AD and BC sections have the form of ellipsoid arcs

$$\frac{r^2}{a_0^2} + \frac{z^2}{b_0^2} = 1$$

and AB and DC sections are the arcs of the hyperbola having one focus with the ellipsoid

$$\frac{r^2}{a_2^2} - \frac{z^2}{b_2^2} = 1$$

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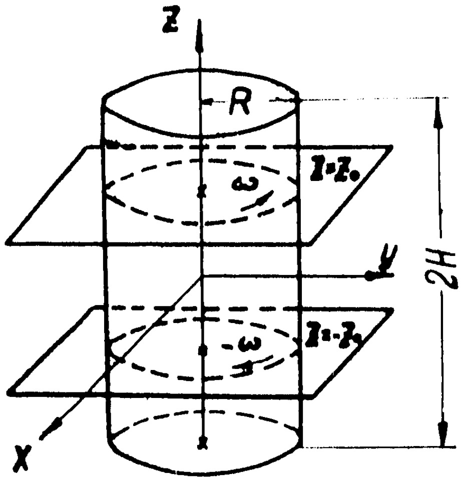

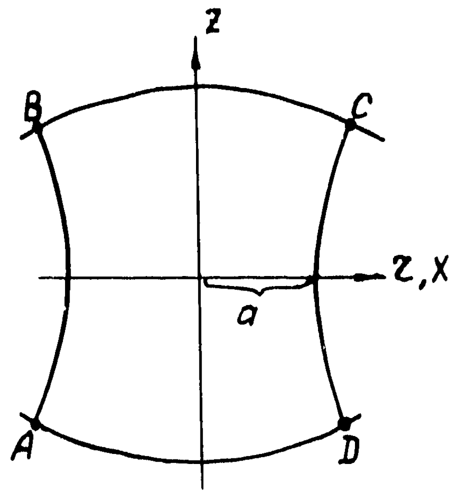

Let the focus distance for the both of the cirves be 2c. It is easy to state for simple geometric considerations that

$$a_2 = a = R\cos\omega$$
$$b_2 = b = z_0 \operatorname{ctg}\omega$$
$$a_9 = \left[H^2 + (a^2 + b^2)\right]^{1/2} = \left[H^2 + R^2\cos^2\omega + z_0^2 \operatorname{ctg}^2\omega\right]^{1/2}$$
$$b_9 = H$$
$$c^2 = R^2\cos^2\omega + z_0^2 \operatorname{ctg}^2\omega$$

Thus the parameters a, b, c of the twisted reactor are completely defined provided the effective height and radius of the cylinder, the rotation angle ω , and the distance between the twisting surfaces 2Zo, are given. The maximum angle of rotation is defined by the contact condition of the fuel elements with the diameter d:

$$\sin\omega \le \left[\frac{1-(d/D)^2}{1+(d/D)^2(R/z_0)^2}\right]^{1/2}$$

D is the cell spacing in the cylindrical reactor (ω = 0).

The boundary problem equation of finding the critical parameter in one-group approximation will be witten as follows:

$$\Delta\varphi + \varkappa^2\varphi = 0 \qquad (1)$$

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$$\varphi / \Sigma = 0 \qquad (2)$$

where φ is the thermal neutron flux, Σ effective reactor surface, $\varkappa^2$ material buckling depending on the space co-ordinates, neutron flux and integral flux.

The nonlinear equation (1) may be considered quasi-stationary.

Either the angle ω or reactivity ρ may be considered the critical parameter of the fuel burn-up problem. As compared with the results of critical experiments, it is convenient to consider the effective radius R the critical parameter and to use in the calculation $\varkappa^2$ value versus the cell area S determined experimentally instead of x^2 value calculated on the basis of geometrical and nuclear lattice parameters. This eliminates possible errors in calculating multiplication factors and this makes it possible to evaluate easily the errors due to approximation in describing a real reactor system by means of one-group model for a reactor of effective sizes.

It is convenient to solve the boundary problem in degenarate ellipsoidal co-ordinates for an oblate ellipsoid of revolution:

$$\begin{aligned} x &= c \operatorname{ch}\alpha \sin\beta \cos\varphi \\ y &= c \operatorname{ch}\alpha \sin\beta \sin\varphi \\ z &= c \operatorname{sh}\alpha \cos\beta \end{aligned} \qquad (3)$$

The co-ordinate surfaces are oblate ellipsoids of rotation, α = const, one sheet hyberboloids of rotation, β = const, the planes φ = const. The Laplacian operator in this system of the co - ordinates has the form:

$$\Delta\varphi = \frac{1}{c^2(\operatorname{ch}^2\alpha - \sin^2\beta)}\left[\frac{1}{\operatorname{ch}\alpha}\frac{\partial}{\partial\alpha}\left(\operatorname{ch}\alpha\frac{\partial\varphi}{\partial\alpha}\right) + \right.$$

$$\left. + \frac{1}{\sin\beta}\frac{\partial}{\partial\beta}\left(\sin\beta\frac{\partial\varphi}{\partial\beta}\right) + \left(\frac{1}{\sin^2\beta} - \frac{1}{\operatorname{ch}^2\alpha}\right)\frac{\partial^2\varphi}{\partial\varphi^2}\right]$$

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Let us confine ourselves to the case when the solution does not depend on the angle φ.
Then the equation (1) will take the form:

$$\frac{1}{ch\alpha}\frac{\partial}{\partial\alpha}\left(ch\alpha\frac{\partial\varphi}{\partial\alpha}\right)+\frac{1}{\sin\beta}\frac{\partial}{\partial\beta}\left(\sin\beta\frac{\partial\varphi}{\partial\beta}\right)+ + c^2(ch^2\alpha-\sin^2\beta)\,\mathscr{x}^2\varphi=0 \qquad (1^{I})$$

It is easy to become sure that

$$S=\frac{\sqrt{3}}{2}\frac{D^2}{R^2}c^2ch\alpha\left[ch\alpha+sh^2\alpha\ln\frac{1+ch\alpha}{\cos\beta_1+\sqrt{sh^2\alpha+\cos^2\beta_1}}-\cos\beta_1\sqrt{sh^2\alpha+\cos^2\beta_1}\right]=f(\alpha)$$

where $\sin\beta_1=\frac{a}{c}$

To use finite differencial scheme it is convenient to introduce variables

$$\xi=1-\cos\beta$$
$$\eta=sh\,\alpha$$

and to transform the equation (1) and the condition (2) to the form

$$\frac{\partial}{\partial\eta}\left[(1+\eta^2)\frac{\partial\varphi}{\partial\eta}\right]+\frac{\partial}{\partial\xi}\left[\xi(2-\xi)\frac{\partial\varphi}{\partial\xi}\right]+ + c^2\left[\eta^2+(1-\xi)^2\right]\mathscr{x}^2(\xi,\eta,t,\varphi)\,\varphi=0 \qquad (1^{II})$$

$\varphi=0$ when $\xi=1-\cos\beta_1$, when $\eta=sh\,\alpha_1=\frac{H}{C}$

$\frac{\partial\varphi}{\partial\eta}=0$ when $\xi=0$ when $\eta=0$ $\qquad (2^{II})$

(In case of numerical solution it is possible to confine ourselves to the quater of the symmetrical figure).

The expression for S in new variables is

$$S=\frac{\sqrt{3}}{2}\frac{D^2}{R^2}c^2(1+\eta^2)\left[\sqrt{1+\eta^2}+\eta^2\ln\frac{1+\sqrt{1+\eta^2}}{\cos\beta_1+\sqrt{\eta^2+\cos^2\beta_1}}-\cos\beta_1\sqrt{\eta^2+\cos^2\beta_1}\right]$$

The nonlinear equation (1") with boundary conditions (2")

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was solved numerically on an electronic computer. The accuracy of the solution was compared with analytic results for special cases of $\varkappa^2$ as a function of the co-ordinates.

3.

The suitability of the mathematical model (1) and (2) was analysed by comparison of predicted data with the experimental results obtained for a set of fuel elements containing enriched to 7% UO_2 encased in aluminium cans. The outside diameter of the fuel rods is 11.4 mm, they are 1200 mm long. The view of two assemblies (one of them "in cross-section") is shown in Figs 1 and 2.

The critical numbers of fuel elements N of those assemblies with different lattice spacing and angles of "twisting": were compared:

$$N = \frac{2\pi}{\sqrt{3}} \frac{(R\cos\omega - \delta)^2}{D^2\cos^2\omega}$$

the δ value describing the reflector saving was considered the function only of the initial spacing D.

The relation $\varkappa^2(S)$ was obtained as a result of experiments on cylindrical systems. The agreement between the predicted and experimental results was quite satisfa[illegible]. The calculated neutron flux distributions along the axis of the assemblies (Figs.3,4) are rather accurate too. They were compared with the distributions obtained by means of a semiconductor crystal surface-barrier counter recording fission fragments from a U-235 target. The discrepancy in the distributions was only for the closely-spaced assemblies twisted thus that the fuel elements nearly touched each other (Fig.5). Obviousl[illegible] this discrepancy was coused by non-ideal geometry of the experiments: the lower boundary of the core was flat and the upper one was too convex. A plexiglass cap used as the bottom reflector considerably reduced the neutron flux distribution asymmetry (see curve 3 in Fig.5) though its curvature was noticeably less than it was necessary for the core to have a regular form.

To calculate the reactivity value compensated by "twisting"

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with a fixed number of fuel elements $\varkappa^2$ in equation (1) was substituted for

$$\varkappa^{*2} = \varkappa^2 (1 - \rho) - \rho / M^2$$

The critical parameter, reactivity ρ, versus ω at two values of the initial spacing D is shown in Fig.6.

In the whole range of $0 \leq \rho \leq 0.09$ the axial non-uniformity of power distribution differs from the initial value for not more than 20%, the deformation of a closely-spaced lattice improving and that of a great spacing lattice worsening neutron flux distribution. The corresponding parameters of volumetric non-uniformity are $\sim$ 30% and $\sim$10%. It should be noted here too that the fuel burn-up process promotes the power distribution flattening.

A second set of experiments was made on channels in the form of a bundle of concentric tubular fuel elements in steel cans inserted one into the other. One of the assemblies is shown in Fig.8. As there is no water in the channel, ρ vs.D had no going down branch at small spacing and it was possible to use only the range D of 70 to $\sim$ 50 mm. The ρ value as a function of ω was studied experimentally. An additional channel was inserted into the critical assembly and reactor period was measured. According to generally used formula the period was transformed into $\Delta\rho$, a change in reactivity in case of an additional charge. The $\Delta\rho$ value as a function of N was integrated numerically with the upper limits of 170, 160... 90, and 85 channels; integral values are shown in Fig.7. Additional experiments were made to evaluate an operation of possible shut-down systems. In particular, the relation between the angle of "twisting" and the quantity of boric acid injected provided N = const = 152 was studied. H_3BO_3 concentration was 0.192 and 0.396 g/litre at $\omega = 15^\circ$ and 20°. These values are very far yet from the solubility limit and this makes it possible to use a small volume of highly concentrated solution injected into the core as a safety means in case of emergency.

The central channel was removed from the same critical assembly and a steel sheath tube, 44 o.d, 36 i.d, was placed instead of it and then a bundle of boron rods, 8.5 mm in dia.each, was inserted into the sheath tube. The experimental results are listed in Table I.

It is obvious that such a bundle or a single rod of the corresponding diameter may be used as an automatic regulator. Simultaneously a programme for design of systems that are two-region in the radial direction was prepared.

It is shown that the radial flux distribution in an assembly with a cavity formed instead of seven central channels removed is quite acceptable. Neutron flux peaking in the cavity influences favourably the efficiency of absorbing rods that are inserted into it, in addition the rods may be fabricated rather thick. Unmovable channels for absorbers may be twisted in advance. The water gap between the absorber zone and the core may give rise to increase in power of the inner ring formed by 12 channels though decrease in nuclear fuel concentration prevents the emergency conditions from ocurring.

The reactor scheme under consideration becomes more complete if fuel channels are in an annular position instead of forming a hexahedral lattice. Each ring should contain the same number of channels as the corresponding row of the hexahedral lattice does, that is 6, 12, 18, etc.

Table I.

$\Delta\rho$ value in terms of 10^{-3}

$\varphi = 2\omega$	20°	30°	45°
Central channel removal	8.6	10.7	11.7
Steel sheath tube insertion	0	0	0
Insertion of boron rods bundle	3.3	4.8	6.3

The distance between the rings is chosen thus that every channel will have an equal water volume. For example, the external ring radius in the direction of the channel axis is $\left[\frac{S}{\pi}\left(N - \frac{n}{2}\right)\right]^{1/2}$ where N is a total number of cells, n a number of cells in the external ring. It was shown experimentally that this deviation from the regular form of cells does not affect the reactivity.

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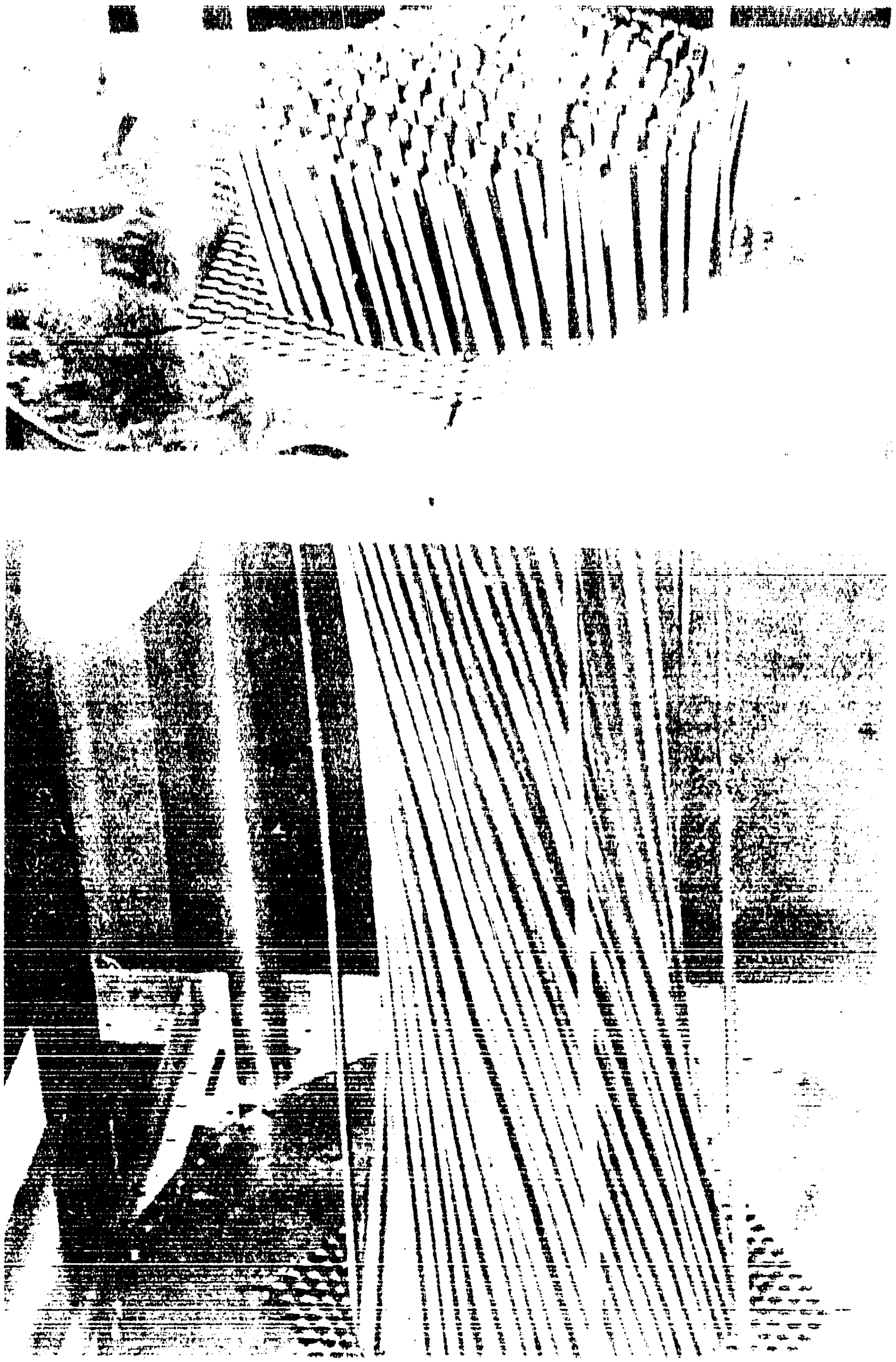

Fig.1. Hyperboloid assembly of fuel rods.

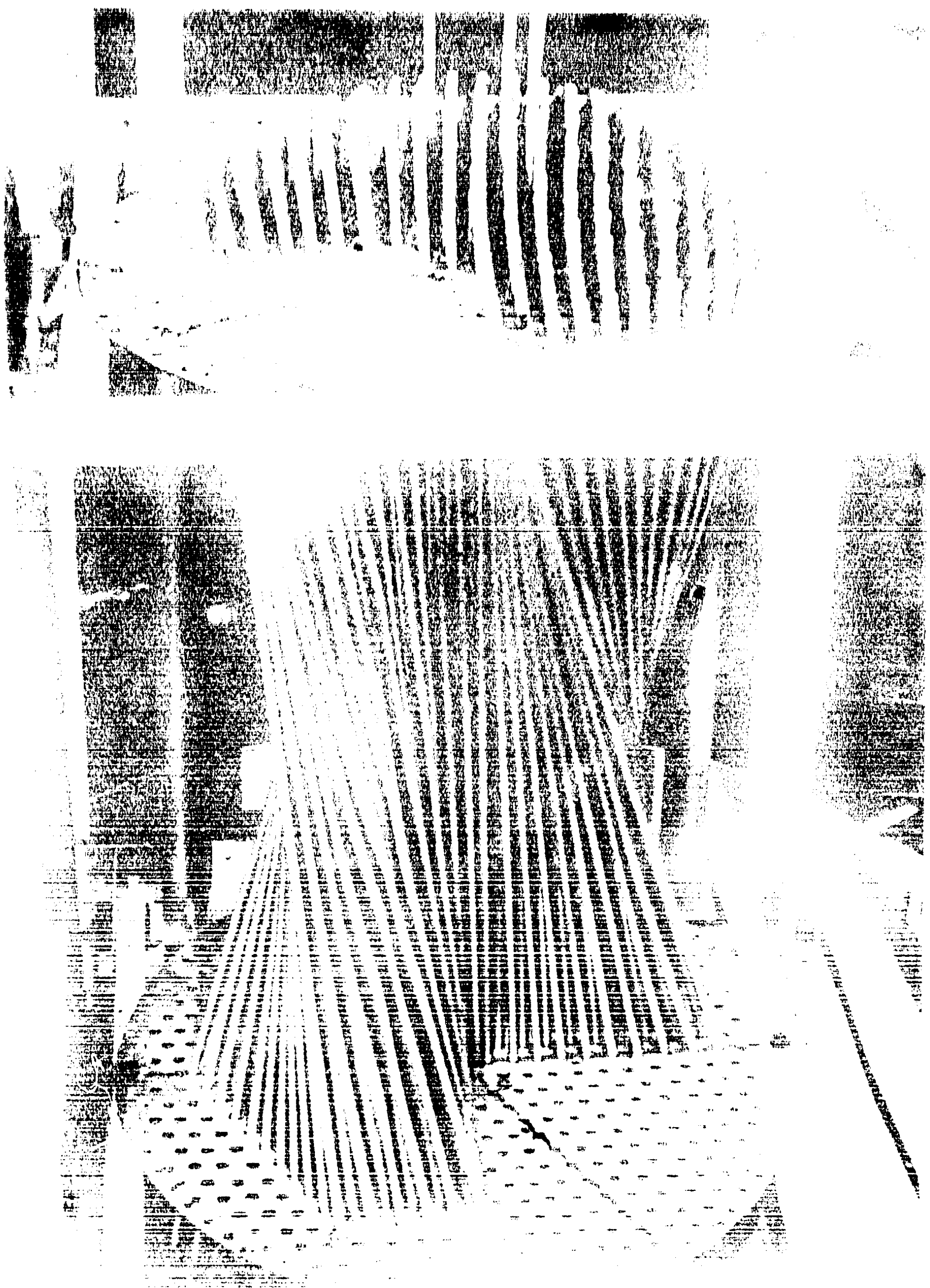

Fig.2. Hyperboloid assembly "cross-section".

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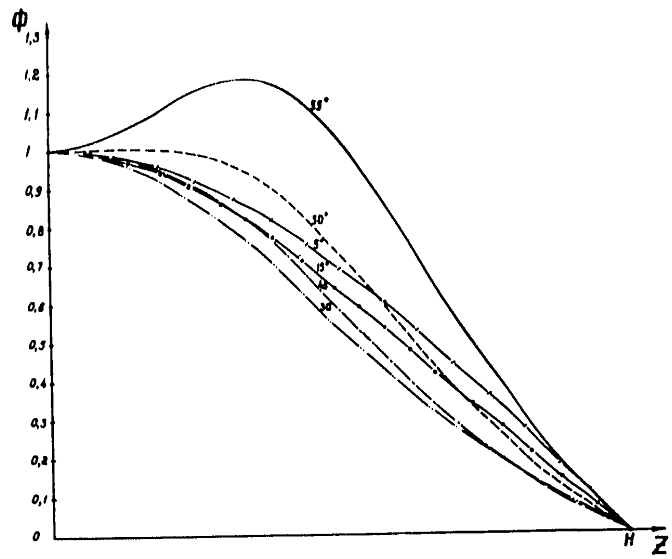

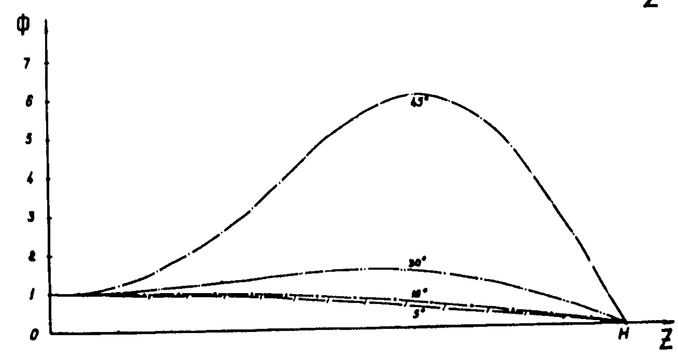

Fig.3. Changes in neutron flux distribution along assembly axis with 3 cm initial spacing while "twisting".

Fig.4. Changes in neutron flux distribution along assembly axis with 1.7 cm initial spacing while "twisting".

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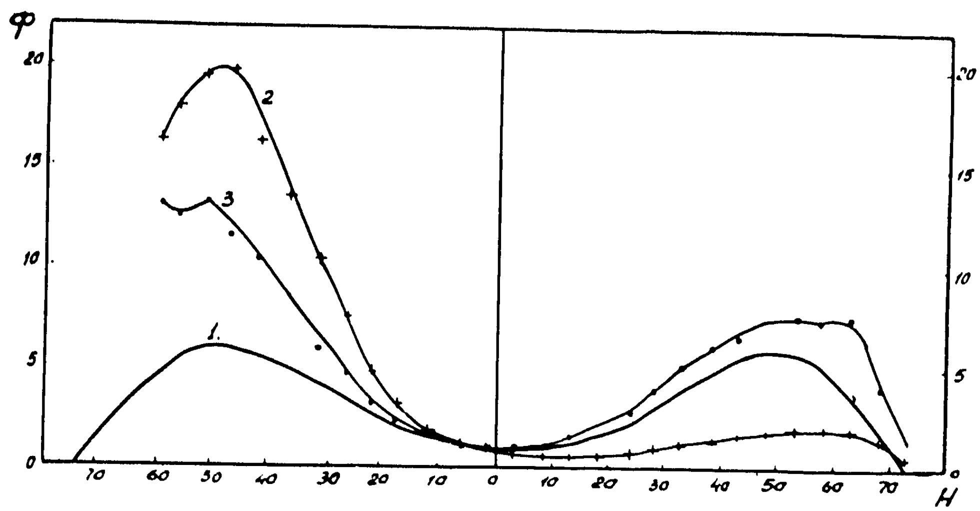

Fig.5. Neutron distribution instability at low and great D values

1. Calculated curve for symmetrical assembly.
2. Flat lower boundary of core.
3. Partially symmetrized assembly.

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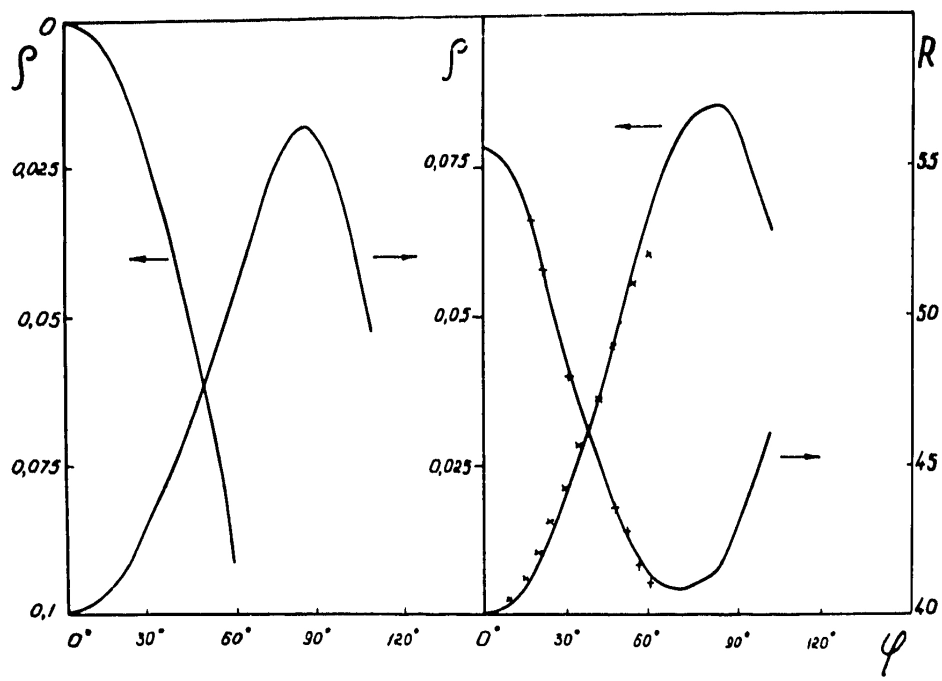

Fig.6. Reactivity vs. angle of "twisting" for two D values ($\varphi = 2\,\omega$).

Fig.7. ρ and R vs. angle of "twisting" while "twisting" channel system with D = 7 cm.

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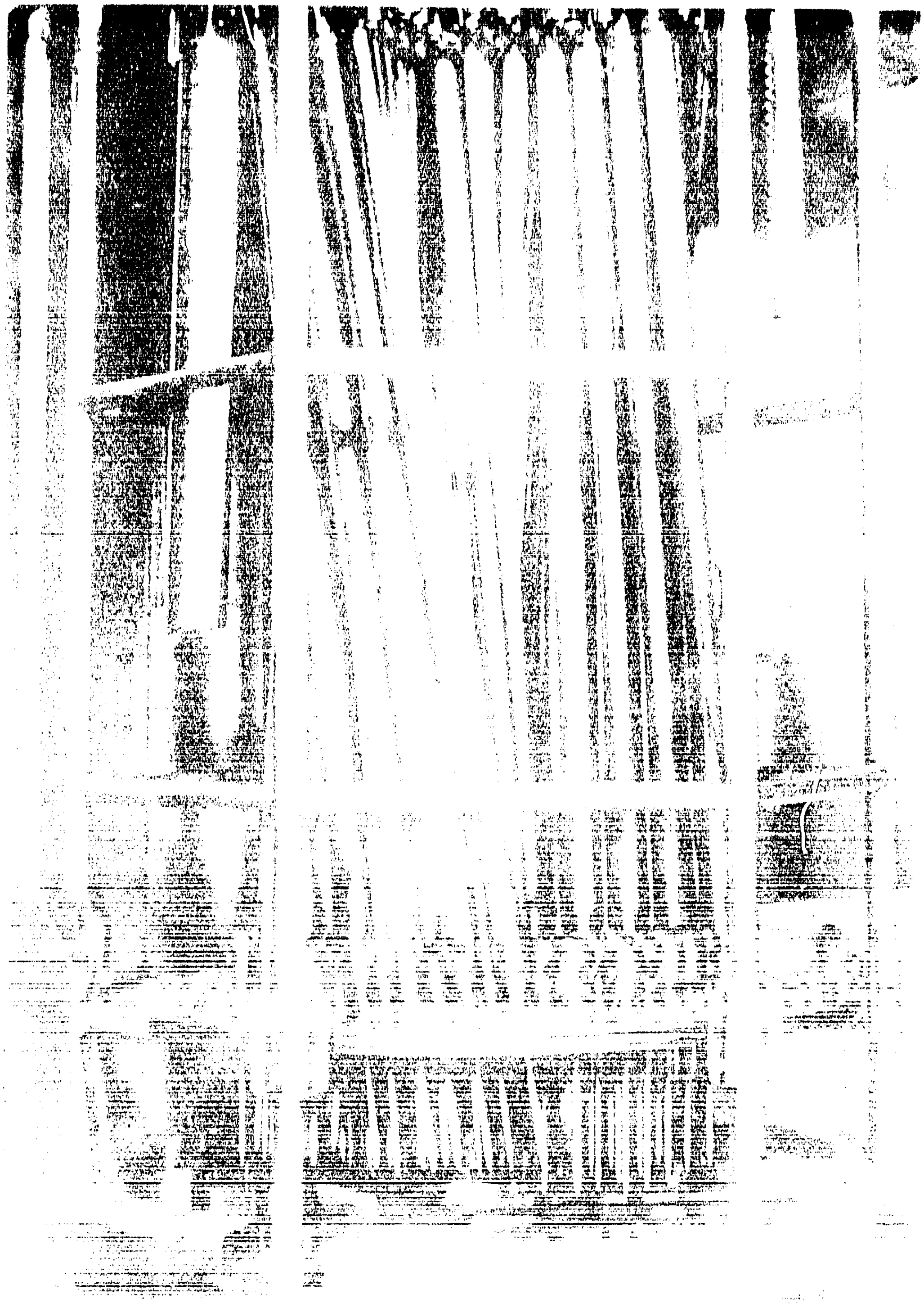

Fig.8. Test rig for studies in hyperboloid assemblies.

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